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Technical Report S-213

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MEASUREMENT OF EROSIVE BURNING RATES

by

Joe M. Viles

Contracts
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REDSTONE RESEARCH LABORATORIES
HUNTSVILLE, ALABAMA 35807

FOREWORD

The work described in this report was performed under Contract DAAH01-67-C-0947 and Contract DAAH01-68-C-0891 for the exploratory development of solid propulsion technology under the technical cognizance of Propulsion Systems Engineering Branch, Army Propulsion Laboratory and Center, Research and Development Directorate, U. S. Army Missile Command.

This work is a portion of a continuing effort to develop and demonstrate usefulness of a new approach for obtaining the erosive-burning characteristics of solid propellants. The technique permits determination of erosive burning rates under realistic motor conditions with only small quantities of propellant, an important consideration when dealing with sensitive, expensive, or toxic materials.

ABSTRACT

A new technique for measuring average erosive burning rates of a propellant fired under realistic motor conditions is described. By utilizing a small test motor attached as a blast tube to a large gas generator, a minimal amount of test propellant is required. Hence the technique is attractive for evaluating or ranking the erosive-burning tendencies of compositions in a propellant development program. Erosive burning rates were measured for a CTPB-based composite propellant. Excellent correlation was found between the erosive burning rate, Mach number at the tail end of the propellant grain, and chamber pressure. The erosive burning rates measured in the test motors were independent of the composition of the gas-generator propellant. Application of the data in the design of an erosive-burning propellant grain has not been made.

CONTENTS

Section I. INTRODUCTION

In a recent program (1)[1], a low-burning-rate propellant for application in a high-L/D, Army rocket was characterized. Since low-burning-rate propellants are more susceptible to erosive burning than high-burning-rate propellants and high-L/D rocket motor configurations are conducive to erosive burning, it was necessary to rank the various compositions according to their erosive-burning tendencies. Accordingly, a simple and fast means of comparing the erosive-burning properties of the candidate propellants was required.

Many experimental and theoretical techniques have been developed since Mansell in 1908 first observed that solid propellants burn faster when subjected to a high flow rate of hot gases parallel to the burning surface and termed the phenomenon "erosion". An excellent review of the bulk of the work on erosivity was given by Zucrow, et al. (2). The experimental approaches for measuring erosive burning rates include interrupted burning tests, photographic techniques (X-ray and direct), light pipes, pressure taps, and thermocouples and other types of wire apparatus embedded in the propellant. The light-pipe technique was selected initially for these studies since it appeared most adaptable to available hardware and instrumentation.

Light probes made from Plexiglas®[2] rods were inserted through the walls of 2 × 4-in. static test motors such that the tips of the rods protruded less than 1/4 in. within the motor. Propellant grains formulated from compositions to be tested were cast into the motors and around the rods using an internal-burning, cylindrical configuration with a web thickness of 1/4 in. Several rods were placed within each motor to permit multiple burning-rate measurements in each test firing. High gas velocities over the propellant surface were attained by attaching the small test motor as a blast tube to a larger gas-generator motor. Two of the many experimental difficulties encountered were: (1) placement of the tip of the light probe at the desired depth in the grain was tedious, and (2) the propellant even when modified by the addition of up to 2% carbon black was translucent to the intense light of the flame zone, making it extremely difficult to determine when the grain surface burned past the tip of the probe.

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[1]Numbers in parentheses indicate references at the end of the report.
[2]Trademark of Rohm and Haas Company, Philadelphia, Pa.

During these probe evaluation tests it was found that the average burning rate of the test grain could be determined readily from the pressure trace. Since the gas-generator web was scaled to burn longer than the test web, the incremental pressure contribution from the test grain was superposed upon that of the gas generator, enabling accurate determination of the burning time of the test grain. In view of the simplicity of the pressure-trace analysis compared to probe determinations of burning rate, the probe approach was abandoned and all determinations were made simply from the pressure-time traces. The technique appears applicable to determination of the relative erosive burning tendencies of propellants. However, the degree to which the data may be used to predict pressure-time history in typical grain geometries subject to erosive burning has not been determined.

Section II. EXPERIMENTAL

Erosive burning rates of case bonded, cylindrical grains fired under realistic motor conditions were measured in a 2 X 4-in. static test motor used routinely at these Laboratories. This is a stainless steel motor of inside diameter 2.0 in. and length 4.0 in. Web thicknesses of $\frac{1}{4}$-in. and $\frac{1}{8}$-in. were used in the tests. High gas velocities across the grain were provided by attaching the 2 X 4-in. motor as a blast tube to the end of a 6-in.-diameter gas-generator motor (Figure 1). A mild-steel adapter having a convergent flow area was used to give a smooth flow of gases from the gas generator into the test grain. This convergent section was not lined, but no problems of erosion or overheating were experienced.

Pressure measurements were made at the head and tail of both gas-generator and test grains. The 2 X 4-in. clamp-type motor (in normal usage the motor is clamped between a firing head and nozzle assembly with O-ring seals at both ends) did not have pressure ports. The pressure at the head of the test grain was taken in the adapter, and a motor extension containing a pressure port was placed between the test motor and nozzle assembly for the tail-end pressure. It was necessary to line the extension section with an ablating, asbestos-filled phenolic to protect the metal from erosion and overheating.

Standard test nozzles containing carbon throat inserts with 45° convergent and 15° divergent half angles were utilized. The velocity of gases across the grain was easily varied by changing the diameter of the nozzle throat. The maximum throat diameter was limited to 1.44 in. because for larger sizes the nozzle housing had insufficient bearing surface to hold the insert in place. A larger throat could have been obtained by redesigning the nozzle.

Cylindrical propellant grains with a 5-in. I. D. and variable length (to give desired pressure) were used in the 6-in. I. D. gas-generator motor. The grains were inhibited on the ends and/or slotted as needed to give near-neutral pressure traces. The burning surface of the gas generator grain was sized to produce an approximate chamber pressure by assuming the test and gas-generator propellants would follow the P-K curve of the gas-generator or driver propellant. As firings proceeded, a P-K curve, where K was calculated as the ratio of the total burning surface (sum of the gas-generator and test-motor burning surfaces) to nozzle throat area, was generated (Figure 2). This curve enabled later firings to be made at more predictable pressure levels.

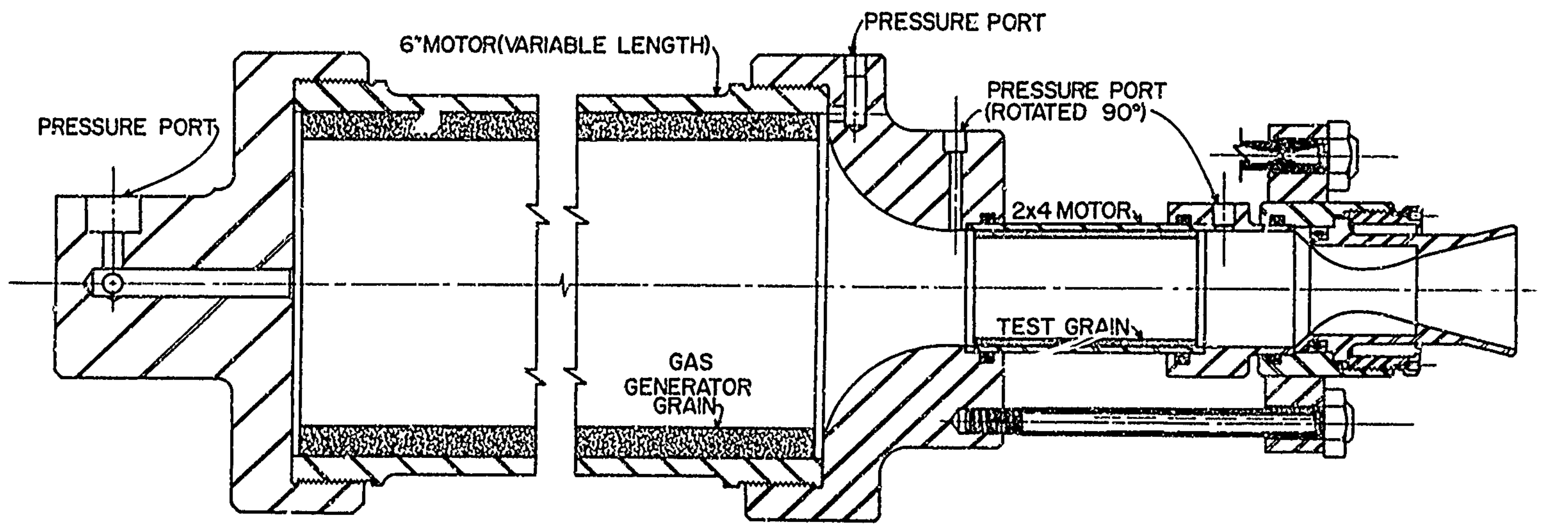


FIGURE 1. EROSIVE-BURNING TEST FIXTURE

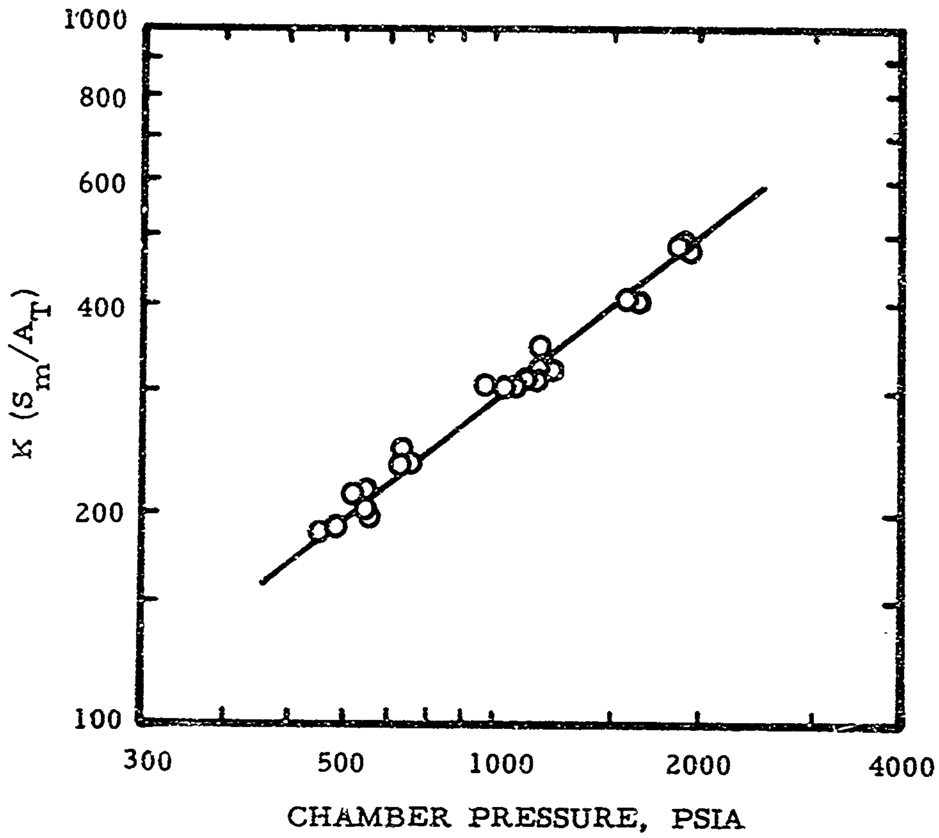


FIGURE 2. P-K CURVE FOR SIZING GAS-GENERATOR GRAIN

The motors were initiated with jelly-roll igniters[3] placed in the 6-in. motors to achieve rapid and uniform ignition of the propellant surfaces. Cellulose acetate throat closures, sized for appropriate expected pressures, were used to give rapid pressure rises in the motors.

The test propellant was a carboxyl-terminated polybutadiene (CTPB) composition containing (by weight) 74% ammonium perchlorate, 12% binder, 10% aluminum and 4% additives. Three propellants were used in the gas generator to determine the effect of the driver composition. One of the three driver compositions was identical to that of the test propellant and had a 3068°K flame temperature. The other two propellants were plastisol-nitrocellulose compositions with flame temperatures within 160° K of that of the test propellant. One contained 10% aluminum and had a 3227°K flame temperature, and the other contained 1% aluminum and had a 2955°K flame temperature.

Since the gas generator maintained a neutral pressure trace by producing a constant mass flow rate until after the test grain had burned out, the pressure trace of the test grain was superposed on that of the gas generator at all four measurement stations as shown in Figure 3. The superposed pressure traces had sharp tail-offs, and the time of test grain burnout was determined by bisecting the tangents to the pressure trace at tail-off. The burning time of the test grain was taken as the time from which the chamber pressure first reached 100 psia until test grain burnout. The average burning rate was determined from the web thickness and burning time. The chamber pressure at each of the four transducer stations was averaged over the burning time of the test grain. The velocity in the test section was expressed as the average Mach number at the tail end of the grain and was calculated assuming an average port area (based on the initial and final areas), a specific heat ratio of 1.2, and isentropic flow.

[3]The jelly-roll igniter is made by spreading a slurry of barium nitrate, powdered magnesium, and potassium perchlorate in a 5% polyisobutylene in n-hexane solution on cheese cloth, drying, and wrapping several layers around an Atlas match.

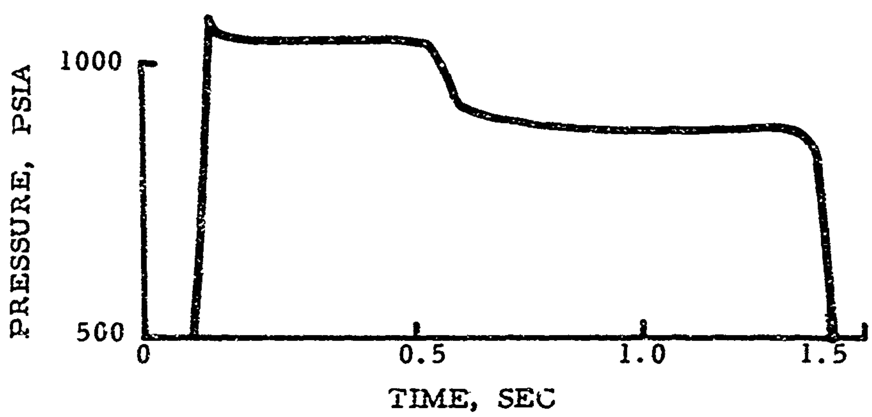


FIGURE 3. TYPICAL PRESSURE TRACE FOR EROSIVE-BURNING FIRINGS

Section III. RESULTS AND DISCUSSION

A dual-grain motor using a large gas-generator grain with a small test grain was used to measure the erosive burning properties of a CTPB propellant over a pressure range of 500 to 2000 psia at Mach numbers from 0.03 to 0.50. Variation of the composition of the gas-generator or driver grain at a relatively constant flame temperature did not affect the erosive burning of the test sample. Although the test was developed for comparative purposes, there appears no reason that the data should not be applicable to erosive-burning predictions in more typical motor configurations.

Normally, under erosive conditions grains burn faster at the exit end where the gas velocity is highest, the change in burning rate along the grain being proportional to the change in velocity. In motors where the velocity does not change significantly along the grain, as in a motor with a throat-to-port-area ratio much less than one, there is no significant change in burning rate along the grain. When the 2 × 4-in. test motor with a ¼-in. web is fired by itself (not attached to a gas generator), the velocity along the grain increases from 0 to approximately Mach 0.03. A one-dimensional isentropic analysis of the gas flow shows the same velocity increases (Mach 0.03 or less) along the grain when the 2 × 4-in. test motor is attached to a gas generator even though the velocities are much higher. This minor change in velocity is due to the low ratio of gases produced by the test motor to gases produced by the gas generator.

Pressure traces with sharp tail-offs (indicative of uniform burnout) supported the above analysis, i.e., near constant velocity along the test section. Additional support was provided by two other experimental observations. High-speed movies of grain burnout in transparent Plexiglas motor cases showed uniform burnout of the test grain. The timely failure of the bolts attaching the test motor to the gas generator provided an interrupted firing test. The extinguished test grain had burned 0.184 ± 0.005 in. at the head and 0.189 ± 0.005 in. at the tail.

The velocity of gases in a motor also changes as the grain is consumed due to the increased flow or port area. The velocity expressed in terms of Mach number (M) at the tail end of the grain, the specific heat ratio (γ) of the gases, the nozzle throat area (A_T), and port area (A_P) is given by Shapiro (3) as

$$\frac{A_T}{A_P} = M \left[\frac{\gamma + 1}{2(1 + \frac{\gamma - 1}{2} M^2)} \right]^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

The port area in the 2 × 4-in. test motor increases 44% with a 1.5-in. perforated grain and 23% with a 1.75-in. perforation, and the Mach numbers decrease accordingly. Typically the Mach number for a 1.75-in. grain would decrease during a test firing from 0.41 to 0.30 (Round 9234 of Table I). During each test the Mach number may be considered to decrease linearly (with less than 3% error) as the port area increases.

In spite of the Mach number variation with time in each test, excellent correlations of burning rates with the chamber pressure and average Mach number at the tail end of the grain were obtained. The data are summarized in Table I. At constant pressure the burning rate of the CTPB composition increased linearly with Mach number (Figure 4). Figure 4 also shows close agreement of data obtained from test grains having 1.5- and 1.75-in. perforations. The slope of the log P—log r curve was constant for constant Mach number and increased with Mach number (Figure 5). The reduced burning rate (ratio of erosive burning rate, r, to non-erosive burning rate, r_0), also plotted in Figures 4 and 5, behaved similarly to the erosive burning rates.

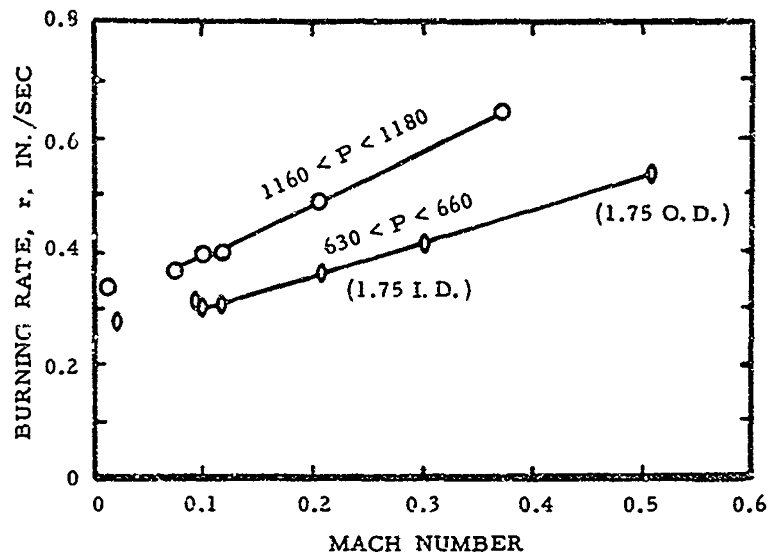
It was not necessary to use the same propellant in the gas generator as in the test motor. Figure 4 shows close agreement between data from tests in which the gas-generator propellant was the same CTPB propellant (10% aluminum) as used in the test motor and two plastisol nitrocellulose composite compositions containing 10% and 1% aluminum. The flame temperature of all gas-generator propellants, however, did not vary more than 160° C from that of the propellant being tested. This flexibility permits evaluation of new compositions by using limited quantities of the propellant.

A few tests were made with a longer (2 × 8-in.) test motor, and no differences were observed between the burning rates obtained in the 2 × 4-in. and 2 × 8-in. motors (Table I). Since the longer motor has a bigger change in velocity along the grain and requires twice as much propellant, little emphasis was placed on these tests.

Table I. Burning-Rate Data for a CTPB Propellant[a] Fired Under Erosive-Burning Conditions

Round No.	A_{TM} (in.^{2})	Gas Generator: Propellant	Gas Generator: S_m (in.^{2})	Gas Generator: Head Pressure (psia)	Gas Generator: Tail Pressure (psia)	Test Grain: I. D. (in.)	Test Grain: O. D. (in.)	Test Grain: L (in.)	Test Grain: Head Pressure (psia)	Test Grain: Tail Pressure (psia)	Test Grain: r (in./sec)	Test Grain: r_o[b] (in./sec)	Test Grain: Mach[c] Number
8769	0.3513	CTPB, 10% Al[a]	51.7	664	613	1.510	2.000	3.7	694	659	0.312	0.278	0.09
8770	0.2240	CTPB, 10% Al[a]	51.7	1232	122[illegible]	1.508	1.999	3.7	1225	1236	0.375	0.345	0.0[illegible]
8771	0.2055	CTPB, 10% Al[a]	69.0	1167	1163	1.510	1.990	3.7	1158	1160	0.364	0.339	0.07
8772	0.7522	CTPB, 10% Al[a]	100.0	556	564	1.510	2.000	7.4	552	539	0.317	0.262	0.20
8773	0.3822	CTPB, 10% Al[a]	100.0	1115	1123	1.511	2.001	3.7	1116	1113	0.392	0.335	0.10
8774	0.2980	CTPB, 10% Al[a]	99.9	1645	1653	1.510	1.881[d]	3.7	1646	1650	0.437	0.380	0.08
8775	0.4419	CTPB, 10% Al[a]	100.0	1154	1155	1.508	1.999	7.8	1166	1145	0.396	0.338	0.12
8776	0.5710	CTPB, 10% Al[a]	191.3	1571	1583	1.510	1.999	3.7	1578	1558	0.487	0.373	0.14
8810	0.3627	CTPB, 10% Al[a]	51.7	----[h]	----[h]	1.508	1.997	3.7	----[h]	652	0.302	0.277	0.10
8811	0.4419	CTPB, 10% Al[a]	68.9	646	645	1.510	1.998	3.7	648	546	0.306	0.276	0.12
8812	0.7514	CTPB, 10% Al[a]	100.0	583	580	1.508	2.000	7.8	585	583	0.327	0.267	0.20
8813	0.4465	CTPB, 10% Al[a]	191.4	1957	1959	1.510	1.998	3.7	1962	1946	0.474	0.400	0.12
8821	1.3310	CTPB, 10% Al[a]	384.7	1070	1076	1.508	2.000	3.7	1039	1054	0.604	0.328	0.37
8827	0.6057	CTPB, 10% Al[a]	100.0	743	745	1.508	2.000	7.8	725	738	0.305	0.289	0.16
8871	1.3293	CTPB, 10% Al[a]	384.7	1019	995	1.510	1.998	3.7	972	995	0.583	0.322	0.37
8873	0.8397	CTPB, 10% Al[a]	388.5	1876	1883	1.509	1.999	3.7	1870	1830	0.669	0.394	0.22
9233	0.9477	CTPB, 10% Al[a]	204.5	770	763	1.748	1.999	3.7	754	730	0.398	0.268	0.21
9234	1.5349	CTPB, 10% Al[a]	310.2	687	675	1.752	1.998	3.7	648	592	0.450	0.267	0.36
9235	1.5360	CTPB, 10% Al[a]	514.6	1195	1216	1.750	1.996	3.7	1160	1053	0.643	0.328	0.36
9463	0.2489	CTPB, 10% Al[a]	101.5	1899	1913	1.750	1.993	3.7	1923	1923	0.454	0.400	0.05
9483	0.1288	CTPB, 10% Al[a]	11.5[e]	728	734	1.752	2.001	3.5	729	----[h]	0.331	0.292	0.03
8814	0.6976	CTPB, 10% Al[a]	191.5	1080	1086	1.510	2.002	3.7	1079	1074	0.438	0.332	0.18
8872	0.9537	CTPB, 10% Al[a]	291.5	1204	1199	1.510	1.995	3.7	1174	----[h]	0.529	0.340	0.26
8994	1.5262	CTPB, 10% Al[a]	309.0	680	679	1.508	1.750	3.7	617	637	0.534	0.275	0.51
8726	1.127	PNC, 1% Al[f]	103.2	596	604	1.510	1.998	7.7	590	543	0.441	0.262	0.29
8727	1.331	PNC, 1% Al[f]	189.8	936	944	1.508	2.002	3.6	915	857	0.569	0.306	0.37
8778	1.128	PNC, 1% Al[f]	99.2	688	687	1.510	2.000	7.7	671	636	0.413	0.276	0.30
8779	0.777	PNC, 1% Al[f]	96.7	1177	1187	1.508	2.000	7.8	1179	1176	0.485	0.340	0.21
8780	1.338	PNC, 1% Al[f]	190.0	1218	1325	1.510	1.997	3.7	1189	1180	0.643	0.342	0.37
9505	1.038	PNC, 1% Al[f]	137.1	857	860	1.752	1.994	3.[illegible]	843	817	0.427	0.300	0.23
9506	0.861	PNC, 1% Al[f]	189.3	1614	1613	1.750	1.997	3.6	1598	1567	0.632	0.373	0.19
9236	1.532	PNC, 10% Al[g]	152.7	622	647	1.752	1.998	3.7	613	549	0.426	0.263	0.36
9237	0.937	PNC, 10% Al[g]	94.0	689	680	1.750	1.996	3.7	674	656	0.361	0.278	0.21
9238	1.524	PNC, 10% Al[g]	185.0	823	824	1.749	2.000	3.7	802	702	0.516	0.283	0.36
9464	1.532	PNC, 10% Al[g]	263.4	1393	1400	1.749	1.996	3.6	1339	1268	0.729	0.348	0.36
9465	1.655	PNC, 10% Al[g]	269.7	1440	1443	1.750	1.996	3.6	1374	1288	0.780	0.350	0.39

[a] A CTPB propellant containing 10% Al and having a 3068° K flame temperature.
[b] Non-erosive burning rate at tail pressure of test motor. The rates were obtained from 2 × 4-in. motor firings.
[c] Average Mach number at t[illegible] end of grain for γ = 1.2.
[d] Blew nozzle and grain extin[illegible]hed.
[e] 2 × 4-in. gas generator.
[f] A plastisol nitrocel[illegible]ulose composite propellant containing 1% Al and having a 2955° K flame temperature.
[g] A plastisol nitrocellulose composite propellant containing 10% Al and having a 3227° K flame temperature.
[h] No pressure due to instrumentation problems.



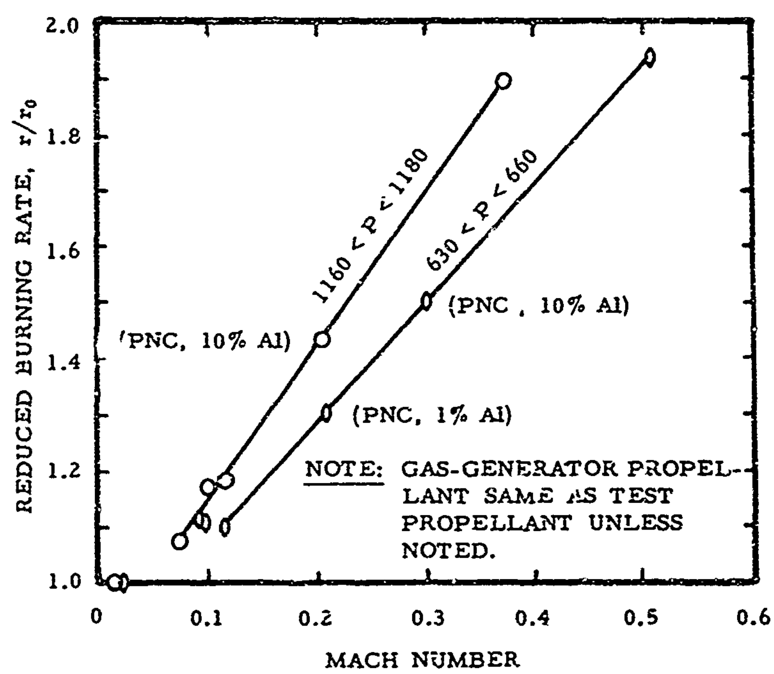


FIGURE 4. EFFECT OF VELOCITY ON AVERAGE BURNING RATES IN MOTORS FIRED UNDER EROSIVE BURNING CONDITIONS

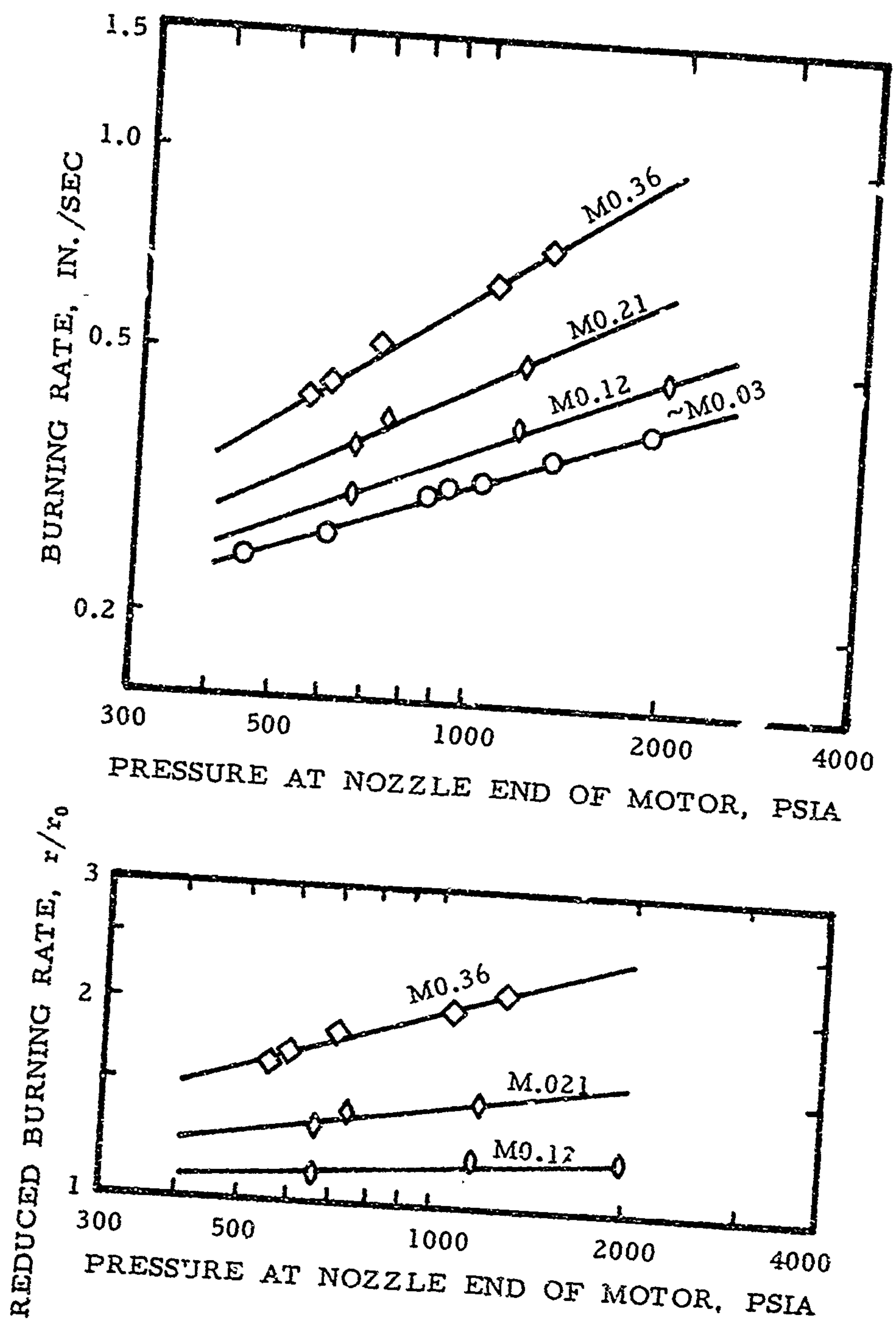


FIGURE 5. EFFECT OF PRESSURE ON AVERAGE BURNING RATES IN MOTORS FIRED UNDER EROSIVE BURNING CONDITIONS

Section IV. SUMMARY

A new technique for measuring average erosive burning rates of a propellant fired under realistic motor conditions was developed. The technique, by utilizing a small test motor attached as a blast tube to a large gas generator, requires a minimal amount of test propellant and is attractive for evaluating or ranking the erosive-burning tendencies of compositions in a propellant development program. Erosive burning rates were measured for a CTPB-based composite propellant. Excellent correlation was found between the erosive burning rate, Mach number at the tail end of the propellant grain, and chamber pressure. The erosive burning rates measured in the test motors were independent of the composition of the gas-generator propellant. Application of the data in the design of an erosive-burning propellant grain has not been made.

Section V. RECOMMENDATIONS

The simplicity of the experimental procedures makes the technique described in this report an attractive means of obtaining erosive-burning-rate data. However, the data reduction procedure produces average burning rates—good only for comparative-type analyses. It is recommended that the data reduction be refined to more accurately define the burning rate as a function of velocity and pressure and that the applicability of these data to conventional grain design be evaluated.

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GLOSSARY

A_P	Cross-sectional area of grain port
A_T	Cross-sectional area of nozzle throat
A_{TM}	Mean cross-sectional area of nozzle throat
CTPB	Carboxyl-terminated polybutadiene
I. D.	Inside diameter of propellant grain
K	Ratio of propellant burning surface to cross-sectional area of nozzle throat
L	Length of propellant grain
M	Mach number
O. D.	Outside diameter of propellant grain
P	Chamber pressure
r	Erosive-burning rate
r_0	Non-erosive burning rate
S_m	Mean burning-surface area
γ	Ratio of specific heats of a gas

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13. ABSTRACT

A new technique for measuring average erosive burning rates of a propellant fired under realistic motor conditions is described. By utilizing a small test motor attached as a blast tube to a large gas generator, a minimal amount of test propellant is required. Hence the technique is attractive for evaluating or ranking the erosive-burning tendencies of compositions in a propellant development program. Erosive burning rates were measured for a CTPB-based composite propellant. Excellent correlation was found between the erosive burning rate, Mach number at the tail end of the propellant grain, and chamber pressure. The erosive burning rates measured in the test motors were independent of the composition of the gas-generator propellant. Application of the data in the design of an erosive-burning propellant grain has not been made.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
CTPB Propellant Erosive Burning Rate of Solid Propellant Gas Generator						